

REPORT DOCUMENTATION PAGE				Form Approved OMB NO. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 13-06-2008		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Oct-2006 - 31-Jan-2008	
4. TITLE AND SUBTITLE Optimizing the Performance of a Condensate Interferometer			5a. CONTRACT NUMBER W911NF-06-1-0474		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 7D10AE		
6. AUTHORS Charles A Sackett			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Virginia Office of Sponsored Programs 1001 N. Emmett St. P.O. Box 400195 Charlottesville, VA 22904 -4195				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSOR/MONITOR'S ACRONYM(S) ARO	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 51925-PH-DRP.1	
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; Federal purpose rights					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT An atom interferometer using Bose-Einstein condensates confined in a magnetic trap has been investigated. Several performance barriers have been studied and overcome. One source of performance degradation is the residual velocity of atoms in the trap. We determined that this motion was largely due to external magnetic field noise, and were able to stabilize it. We have also developed novel coupling techniques that reduce sensitivity to residual motion. A second performance obstacle was spatial noise in the coupling laser beam. This was determined to come from vacuum-cell windows of insufficient quality, and was remediated with a better cell. These improvements led to a factor-of-two improvement in both interferometer					
15. SUBJECT TERMS Bose-Einstein condensation, matter wave interferometry					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Charles Sackett
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER 434-924-6795

Report Title

Optimizing the Performance of a Condensate Interferometer

ABSTRACT

An atom interferometer using Bose-Einstein condensates confined in a magnetic trap has been investigated. Several performance barriers have been studied and overcome. One source of performance degradation is the residual velocity of atoms in the trap. We determined that this motion was largely due to external magnetic field noise, and were able to stabilize it. We have also developed novel coupling techniques that reduce sensitivity to residual motion. A second performance obstacle was spatial noise in the coupling laser beam. This was determined to come from vacuum-cell windows of insufficient quality, and was remediated with a better cell. These improvements led to a factor-of-two improvement in both interferometer visibility and interaction time. Further investigation has determined that performance is now limited by the axial confinement of the magnetic trap. Work is underway to design a new trap with less confinement.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

High-fidelity manipulation of a Bose-Einstein condensate using an optical standing wave, K. J. Hughes, B. Deissler, J. H. T. Burke and C. A. Sackett, Phys. Rev. A 76, 035601 (2007).

Far-off-resonant ring trap near the ends of optical fibers, Frank Moscatelli, Charles Sackett, Shengwang Du and Eun Oh, Phys. Rev. A 76, 043404 (2007).

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

An experiment to measure the electric polarizability of ^{87}Rb using a condensate interferometer. Benjamin Deissler, K. Jeremy Hughes, John H.T. Burke, Cass Sackett. 38th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, June 5–9, 2007; Calgary, Alberta, Canada.

Obtaining a high-visibility Bose-Einstein condensate interferometer. K. Jeremy Hughes, Benjamin Deissler, John H.T. Burke, Cass Sackett. 38th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, June 5–9, 2007; Calgary, Alberta, Canada.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Confinement effects in a guided-wave atom interferometer with millimeter-scale arm separation, J.H.T. Burke, B. Deissler, K.J. Hughes, C.A. Sackett. Submitted to Physical Review A.

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
K. Jeramy Hughes	0.25
Benjamin Deissler	0.17
FTE Equivalent:	0.42
Total Number:	2

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Charles Sackett	0.08	No
FTE Equivalent:	0.08	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PhDs

<u>NAME</u>
Benjamin Deissler
Total Number: 1

Names of other research staff

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

The object of this award was to understand and improved the performance of our condensate interferometer. Devices of this sort are expected to have important applications for inertial measurement, but significant performance advances will be required for this application.

Our interferometer operates using atoms confined in a magnetic guide [1, 2]. Briefly, we produce a condensate of ^{87}Rb atoms, load it into the guide, and then apply an off-resonant standing-wave laser. For the appropriate timing and intensity, this laser causes the condensate wave function to split into two packets traveling apart at roughly 12 mm/s. After a variable time, the laser is applied again with slightly different parameters such that the atomic velocities are reversed and the packets are reflected back towards each other. We allow the packets to cross and then separate again, reflect them once more, and allow them to meet at the center. We then apply the laser a final time in the same way as for the initial “splitting” pulse. This brings some of the atoms back to rest while some continue moving, with the relative populations depending on the interferometric phase difference between the packets. In this way, the phase can be measured.

Prior to the start of this award, we were able to operate the interferometer with total separation times up to about 45 ms, and with an interferometric visibility of about 0.5. We have now extended that time to 80 ms and improved the visibility to about 0.9. Further, we have a clear understanding of what is currently limiting our separation time and have developed plans to extend it. Applications in inertial navigation will likely require separation times on the order of 1 s.

Several factors led to the improvements in performance. The most significant was the realization that multiple reflections from the vacuum cell windows cause significant intensity variations in the standing wave laser beam. This was remedied by obtaining a new cell with anti-reflection coated windows. The capability to manufacture vacuum cells with fully coated windows is very new. To our knowledge, we were the first group to make use of it for ultracold atom applications.

The improvement in performance and reliability with the new cell was immediate and remarkable. We can now apply the standing-wave beam with sufficient precision to split and reflect the condensate with about 98% accuracy. This permitted a detailed investigation of the standing wave interactions, which were found to accurately agree with theoretical expectations. This work has been accepted for publication in Phys. Rev. A. We have subsequently extended it by developing new pulse sequences that permit even greater accuracy and have less sensitivity to the initial atomic velocity.

An additional benefit of the new cell is improved measurement sensitivity. The same effects that limited the standing-wave performance contributed noise to the absorption images used to measure the final state populations. Using coated windows improved the image quality dramatically. We also obtained a new higher-speed imaging camera. The higher speed significantly enhanced our data rate, and also allowed better noise cancellation between the images of the atoms and a subsequent reference picture. Between these two improvements, we have increased our sensitivity to atom number by a factor of ten. We can now detect about 100 atoms, or 1% of the total population.

Having a second camera also allowed us to image the atoms from two directions at once. This permitted us to accurately align the standing wave laser to the axis of the magnetic guide. If this alignment is poor, the laser excites atomic motion in the transverse directions, and the packets will generally miss each other upon returning, by an amount that grows rapidly with the separation time. The visibility of the interferometer is proportional to the overlap of the packets, so this limits the separation time. As it occurred, the alignment was off by about 5 degrees, considerably more than expected. We were able to adjust the laser beam to correct for it.

Another limiting factor we discovered was the presence of noise in the guide magnetic field. Our current source for the field is intrinsically very stable [3], but noise is introduced when we apply external modulation to control the field. We reduced this problem by constructing a new low-noise modulation circuit. Further improvement would be possible with a digital modulation system.

Finally, we encountered difficulties with vibrations of the optical table on which the experiment is mounted. Over the course of the separation time, the table must be stationary on the scale of the standing-wave laser period, which is 390 nm. This level of stability is normally provided by the vibration isolation of the table's air-cushion legs. However, at one point an electronics rack was accidentally pushed into the table, leading to increased vibrational coupling and noise. This was a challenging problem to diagnose, but it does illustrate that the device is a sensitive accelerometer. We have now implemented a constantly running vibration sensor on the table to eliminate such problems.

The results of all these improvements are shown in Fig 1, which shows the interferometer visibility as a function of separation time. For comparison, Fig. 2 shows our previous results.

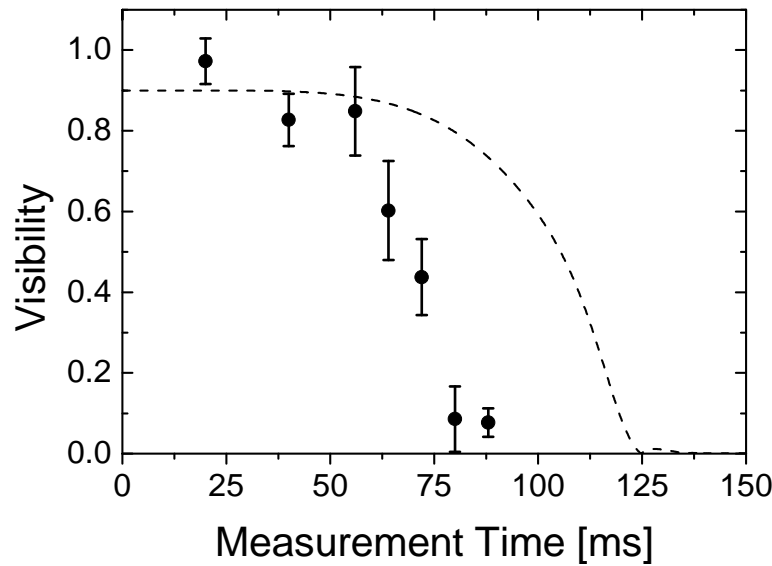


Figure 1: Visibility of interference signal for double-sided interferometer, as a function of total measurement time. The dashed curve is a prediction by Zozulya et al. [7]

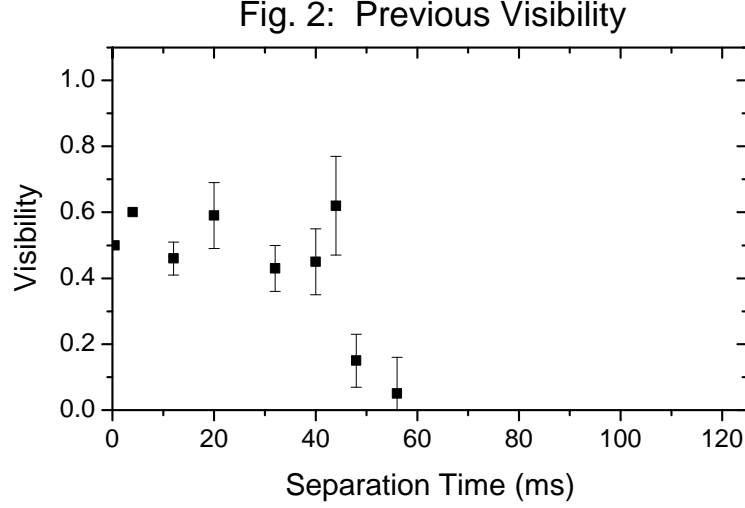


Figure 2: Visibility of interference signal as measured prior to the improvements discussed here.

We believe that the decay of the visibility seen in Figure 1 comes from the fact that the magnetic guide has some weak axial confinement. The basic effect can be understood by considering a single-sided interferometer where the atoms are only reflected once. The initial splitting pulse produces atoms moving at $\pm v_0$, and the reflection pulses provide a kick of $2v_0$, so that $+v_0 \rightarrow -v_0$ and $-v_0 \rightarrow +v_0$. However, if the atoms are subject to axial confinement, then the packets will slow down as they move away from the center. If the speed is reduced by an amount δ , then the reflection pulses will actually drive $+v_0 - \delta \rightarrow -v_0 - \delta$ and $-v_0 + \delta \rightarrow +v_0 + \delta$. When the atoms return to the center, their velocities will now increase by approximately δ , giving final velocities of $\pm(v_0 + 2\delta)$. The recombination pulse again provides kicks of $\pm v_0$, leaving packets with velocity of $\pm 2\delta$.

These two packets do interfere. An atom with velocity v in the x direction is represented by a plane wave $e^{imvx/\hbar}$ for mass m . So the total wave produced by the recombination pulse is

$$\psi = \frac{1}{2} \psi_0(x) \left(e^{2im\delta x/\hbar} + e^{i\phi} e^{-2im\delta x/\hbar} \right) = \psi_0(x) \cos\left(\frac{2m\delta x}{\hbar} - \frac{\phi}{2}\right)$$

where $\psi_0(x)$ is the wave function of the initial condensate and ϕ is the interferometer phase. If $\delta=0$, then the fraction of atoms brought back to rest is $\cos^2(\phi/2)$, the normal interferometer signal. But if $\delta \neq 0$, the population oscillates with period $\hbar/2m\delta$. If this period is long compared to the length of the initial wave packet, it has no appreciable effect. But if the period is shorter than the packet length, different parts of the packet will recombine with different phases, so that the total number of atoms left will be independent of ϕ . By this mechanism, the interferometer visibility is reduced as δ grows.

We were able to verify this effect directly by observing the spatial variation of the atom number in the absorption images. The period of the oscillation agrees well with the calculation. This effect is a significant limitation for a single-sided interferometer, as has been recognized for some time [4-6]. The effect is reduced for a double-reflect interferometer, since the velocity error for the second half-cycle partially cancels that of the first half-cycle. We were able to

observe this directly by monitoring the spatial phase gradient while varying the duration of the second half-cycle. The results are shown in Fig 3. The first half-cycle duration was 20ms, and when the second half matches the first, the phase gradient is suppressed. When the two halves are unequal, however, a significant gradient is present. For longer separation times, the phase gradient is significant even for a symmetric interferometer, giving the effect plotted in Fig. 1.

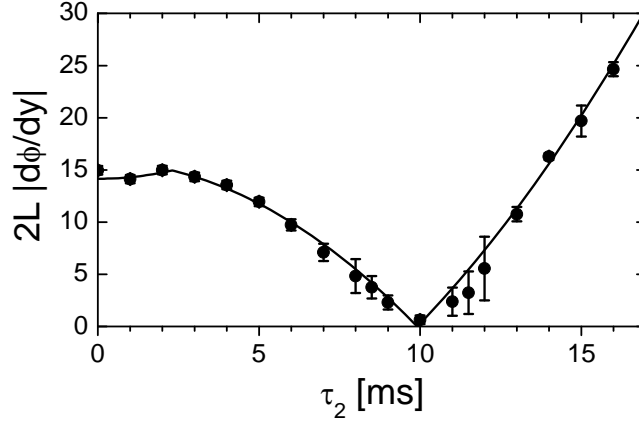


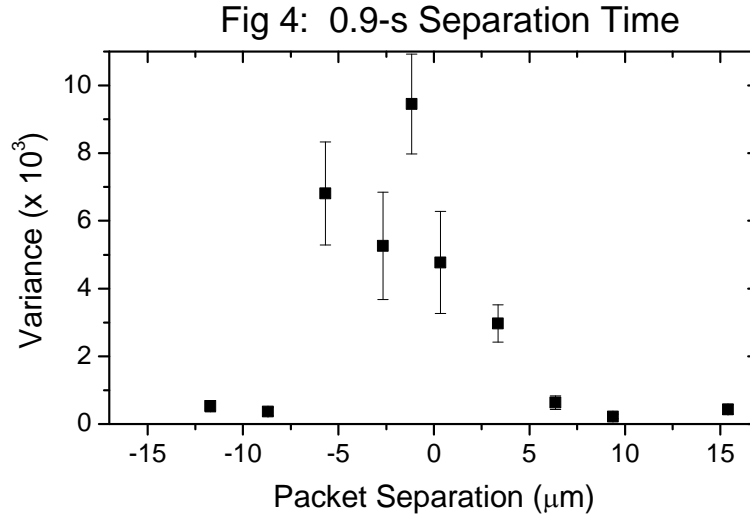
Figure 3: Phase gradient of an asymmetric double-sided interferometer.

To demonstrate that this is not a fundamental limitation, we operated a very long-time interferometer using no reflection pulses. If the splitting pulse is applied and the atoms are allowed to move naturally, the axial potential eventually slows them down and sends them back to the origin. We allowed the atoms to complete a full oscillation cycle of 0.9 s in this way, and then applied the recombination pulse. At such long times, uncontrolled phases can be introduced by many effects such as table vibrations, magnetic field drifts, and atomic interactions. The output of the interferometer is therefore essentially random. However, the fact that the number of atoms brought to rest fluctuates from shot to shot indicates that interference is definitely occurring. Figure 4 shows the variation in the final number as the alignment of the standing wave beam is adjusted. For a misaligned beam, the packets miss each other and not interference occurs, but when the beam is aligned the fluctuations grow. The magnitude of the fluctuations corresponds to that of a random interferometer with a visibility of 0.4.

With this understanding, it is clear that further progress will require a guide with less axial confinement. We are working on developing such a guide.

Two additional results are worth commenting on. The first was an attempt made at implementing a rotation-sensing Sagnac interferometer. The atoms were initially excited in motion transverse to the guide, so that they were oscillating perpendicular to the standing wave laser. At the appropriate time, the atoms would be split, so that as they moved back and forth along the guide they also traced out a closed path in space. With a 60 ms interaction time, an enclosed area of about 1 mm^2 can be obtained. Unfortunately, we found that the splitting pulse did not work correctly when the atoms were moving transversely. It is not clear why that should

be, and we did not have time to resolve the issue. However, it is something we plan to explore further in the future.



Finally one other result is the product of a collaboration between the University of Virginia, Swarthmore College, Stanford University, and the Naval Research Laboratory. This work was triggered by a discussion of atom gyroscopes and ring-shaped traps. It led to the development of a proposal for creating microscopic ring traps using off-resonant light near the end of an optical fiber. Experimental work towards implementing this idea is underway at NRL. The theoretical development has been accepted for publication in *Phys. Rev. A*.

To summarize, during the current award we have identified and solved a number of problems relating to our condensate interferometer, including beam degradation due to uncoated windows, beam alignment, magnetic field noise, and table vibration. We have identified confinement effects as the major remaining limitation, and are developing plans to remediate this as well. So far, we have improved both the interferometer visibility and separation times by a factor of two; we look forward to continuing such improvements until the feasibility for applications can be demonstrated.

References

- [1] J.M. Reeves, O. Garcia, B. Deissler, K.L. Baranowski, K.J. Hughes, and C.A. Sackett, "A time-orbiting potential trap for Bose-Einstein condensate interferometry," *Phys. Rev. A* **72**, 051605(R) (2005).
- [2] O. Garcia, B. Deissler, K.J. Hughes, J.M. Reeves and C.A. Sackett, "Bose-Einstein condensate interferometer with macroscopic arm separation," *Phys. Rev. A* **74**, 031601(R) (2006).
- [3] K. L. Baranowski and C. A. Sackett, "A stable current source for magnetic traps," *J. Phys. B: At. Mol. Opt. Phys.* **39**, 2949-2957 (2006).
- [4] M. Olshanii and V. Dunjko, "Interferometry in dense nonlinear media and interaction-induced loss of contrast in microfabricated atom interferometers," preprint arXiv:cond-mat/0505358 (2005).
- [5] M. Horikoshi and K. Nakagawa, "Dephasing due to atom-atom interaction in a waveguide interferometer using a Bose-Einstein condensate," *Phys. Rev. A* **74** 031602 (2006).

[6] J. A. Stickney, D. Z. Anderson, and A. A. Zozulya, "Increasing the coherence time of Bose-Einstein condensate interferometers with optical control of dynamics," *Phys. Rev. A* **75** 063603 (2007).

[7] J. A. Stickney, R. P. Kafle, D. Z. Anderson, and A. A. Zozulya, "Theoretical analysis of a single- and double-reflection atom interferometer in a weakly confining magnetic trap" *Phys Rev A* **77** 043604 (2008).